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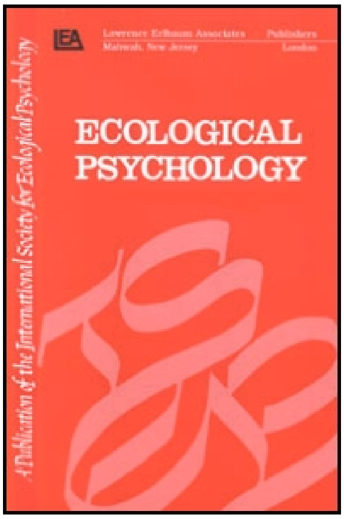

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Stimulus–Response Compatibility Is Information–Action Compatibility

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Stimulus–response compatibility experiments usually employ simple stimuli (e.g., colored lights) and simple responses (e.g., keypresses). The ecological approach to perception and action, on the other hand, emphasizes higher order quantities, information, and action. The three choice reaction time experiments reported here demonstrate the utility of the higher order descriptors for understanding compatibility effects. In Experiment 1, proximal–distal responses were shown to be compatible with the approach–withdrawal information embodied in a two-dimensional kinematic pattern. In Experiment 2, compatibility effects reflected unique combinations of stimulus location, geometric information about distance, and the response. In Experiment 3, a compatibility effect was shown to be a function of an action rather than a mere movement. These results favor an informational description of stimuli and emphasize the functional significance of responses.

The ecological approach to perception and action holds that, given some intention, action is guided by information. Various parameters of actions are expected to be tightly bound to parameters of stimulation (see Warren, 1988, for an overview). The line of research we are pursuing assumes that movement initiation time can be used to probe these relations. As such, differences in reaction time (RT) under different mappings—stimulus–response (S–R) compatibility—are not to be seen as reflecting durations of different information-processing stages, but as instances of a more general perception–action coupling as envisioned by proponents of the ecological approach (Gibson, 1979/1986; Michaels & Carello, 1981; Turvey, Carello, & Kim, 1990; Warren, 1988).

The preferred level of analysis for an ecological approach is at the level of the physical characteristics of the environment taken in reference to an animal's

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possibilities for action, that is, the scale of the ecosystem. Information, in the ecological sense, consists of geometric or kinematic patterns that are lawfully related to the environment, and coordinated action, in the ecological sense, requires the assembly of a number of subsystems into a collective that satisfies the constraints imposed on the organism by the task and by the environment (Turvey, 1990). The patterns that are picked up by an organism serve as a constraint on the actions. Researchers adopting this perspective attempt to identify the appropriate low-dimensional descriptors of information, perception, and action, and how they are lawfully and reciprocally related. An appropriate analysis of "stimuli" requires discovering the macroscopic properties of structured energy distributions in the environment, and how these properties constrain, and are constrained by, the actions of the organism. Relatedly, an analysis of "responses" requires a conceptualization of movements as the outcome of a reduction in the number of motor system degrees of freedom, where the action degrees of freedom are constrained not only by information but also by the task demands, and, importantly, by the intentions of the actor (Michaels & Stins, 1997). Following this line of thought, S–R compatibility phenomena (RT differences obtained with different S–R mappings) are thought to reflect the extent to which the available information can guide the action.[1] Thus, we have proposed to call a situation "compatible" if the information is appropriate to the needs of coordination. For example, Bootsma (1989) had participants return a table tennis smash using one of three action modes. In one, participants used an actual table tennis paddle; in another, they had to operate a mechanical arm that returned the smash; and in the third, they had to press a key. He found that the variability of the movement time increased as the compatibility of the task decreased (paddle to arm to button).

The ecological approach has a long-standing tradition of trying to identify the structures in the stimulus that can serve as a basis for perception (or, more recently, action). A distinction is drawn between observables in the optic array that are variantly related to environmental characteristics and those that are invariantly related to environmental characteristics. The general goal for an ecological psychologist is to determine which of the available observable properties specify salient environmental facts, and then to ask whether perception (or action) appears to be a function of these variables.

[1]This view is different from the more typical information-processing approach to compatibility, which uses RT differences to elucidate cognitive operations that are being performed on a set of stimulus elements (position, relative position, color, etc.) to produce a response. We acknowledge that there is no such thing as *the* information processing approach to compatibility, because at present there are a number of discernible theories of SRC, such as Kornblum's dimensional overlap model, the coding approach, and the attention-shifting account (e.g., Kornblum, 1995; Reeve & Proctor, 1990; Umiltá & Nicoletti, 1992). However, one important aspect that distinguishes these approaches from ours is that they place emphasis on the representational, instead of the informational, characteristics of a stimulus pattern.

In a similar vein, one might argue that a response also admits to several descriptions, and that, presumably, one low-dimensional descriptor captures "what participants are actually doing" when they produce a certain response. Such a description would include the goal-directedness of the act, instead of displacements of a particular limb in an arbitrary coordinate system. For example, in an experiment that involved pressing a left or a right key with one of two handheld sticks, in response to a left or a right visual stimulus, Riggio, Gawryszewski, and Umiltá (1986) found that RT advantages were a function of the spatial correspondence between response key and stimulus, instead of the correspondence between responding hand and stimulus (see also Wallace, 1971). Thus, in Riggio et al.'s situation, the action presumably consisted of responding at a particular place by means of manipulating a stick that served as an extension of the hand. From an ecological perspective, movements are inherently relational activities, aimed at exerting a certain influence on the environment. We therefore propose a description of "responses" in environment-referential instead of environment-neutral terms, as a parallel to the ecological distinction between animal-referential and animal-neutral information (e.g., Warren, 1984). Put another way, a response is not so much what one may do to one's body, but what one does to the world (see also Hommel, 1993). Such a description lays a natural basis for the "R" in S–R compatibility phenomena.

Our goal in the present article is to explore some of the consequences of these ecological emphases as they bear on S–R compatibility (see also Michaels, 1988, 1993; Michaels & Stins, 1997). We want to make clear, however, that our experiments are not intended to distinguish between an information-processing approach and an ecological approach to compatibility. Instead, we hope to demonstrate that a view of compatibility *qua* perception–action coupling opens the door to a host of new variables that might account for RT differences.

The ecological considerations of S–R compatibility outlined above served as a starting point for performing three choice RT experiments. In the first, we attempted to determine the description of stimuli appropriate to capture a compatibility effect observed with a kinematic display. In the second, we asked whether an information collective assembled out of two stimulus dimensions that by themselves were arguably noncompatible with the response (i.e., neither compatible nor incompatible in the terminology of Kornblum, Hasbroucq, & Osman, 1990), enters into a compatibility relation. In the third, we aimed at finding a proper description of a response when a particular limb movement could be understood as constituting different actions.

EXPERIMENT 1

A stimulus can be measured by a number of yardsticks, and it is an empirical question as to which description best captures the characteristic(s) that is (are) most relevant to quick action initiation. An expanding square, say, may be characterized in terms of relatively low-level image characteristics: its initial size, its final size, the duration of its expansion, and so forth. It could also be measured in terms such as its expansion velocity or even in terms of a ratio of momentary size to expansion velocity (the definition of tau; Lee, 1976). Some of these variables are specific with respect to events (e.g., tau, given certain boundary conditions, specifies time to contact), whereas others (momentary image size) are not specific with respect to events.

To the extent that a perceiver detects the information embodied by an expansion or contraction pattern (viz., the specification of an approaching or receding object), a compatibility effect is expected for proximal–distal responses, because these may be said to be symmetrical to the "direction of motion" of the object. A proximal response to an "approaching" square, and a distal response to a "receding" square should constitute compatible actions, whereas the converse mapping should constitute incompatible actions.

Second, we were interested in whether different types of responses (anterior and posterior movements vs. responses at proximal and distal places) would differ in the extent to which they exhibit compatibility effects with the expanding or contracting stimuli. To this end, we compared unimanual joystick deflections with bimanual keypresses. Proximal and distal buttons and a pulled or a pushed joystick share a common "pole" on the proximal–distal dimension, in that pushing a joystick presumably is somehow similar to pressing the distal response key (both can be thought of as an action away from the body). If an emphasis on a common response code (e.g., the end position of the movement or its relative location) is correct, then one would expect the size of the compatibility effect (if any) to be the same in both conditions. However, if the two actions enter into different compatibility relations with the stimulus, then one could infer that they are functionally dissimilar in these two tasks. A smaller compatibility effect might be expected for the position-dependent keypresses than for the movement-related joystick deflections, because only the latter action parallels, in some sense, the specified movement of the distal object.

Method

Participants and design. Sixteen students at the Vrije Universiteit were paid to participate. They had to pull or push a joystick in response to the expansion or contraction of a square, or they had to press a proximal or distal button. For the joystick, there were two mapping rules: Expand–pull/contract–push, and expand–push/contract–pull. Similarly, the mapping rules for the buttons were expand–proximal key/contract–distal key, and expand–distal key/contract–proximal key.

Apparatus and stimuli. An AMIGA computer presented an outline square that either expanded or contracted from its initial size (3.5 cm) in simulation of a 4.7 cm square located 10 cm behind the screen moving at a velocity of 46 cm/sec toward or away from a projection point 30 cm in front of the screen. The square either expanded or contracted in a succession of eight frames until its disappearance when it reached its final size. The movement duration was 160 msec. Directly in front of the monitor was either a joystick that the participant was to push or pull, or there were two response buttons aligned in the proximal–distal dimension. The height of the joystick was about 13 cm. A forward–backward deflection of about 7 mm of the top end of the joystick activated a microswitch inside the joystick. The moment of activation of this microswitch was registered by the computer and was used as a measure of RT. The distance between the two response buttons was 10 cm. The distance between the distal button and the monitor was 10 cm, and the distance between the joystick and the monitor was 15 cm. Data registration and trial generation were controlled by an IBM computer that was connected to the AMIGA.

Procedure. A trial began with the presentation of a centrally located fixation square. At the end of a 1-sec foreperiod, the square either expanded or contracted, and participants were required to push or pull the joystick in response to the stimulus, or they had to press one of the buttons with the finger that rested on it: the index finger of the left or right hand. If the participant's response was correct, a 2.5-sec intertrial interval preceded the next trial. If the response was incorrect, the response was followed by a beep and a 3.5-sec time out.

Eight participants performed the first half of the experiment with the joystick, and the second half of the experiment with the buttons. This order was reversed for the other participants. With the joystick response, the responding hand was changed halfway through the block, so that each participant performed the joystick responses with both hands; for the button presses, the hand operating the proximal key and the hand operating the distal key were reversed halfway through the block. Within each of these sub-blocks, participants received both mapping rules in blocks of 50 trials, resulting in a total of 400 trials.

Results. Errors and RTs that exceeded 1,000 msec (together 4.6%) were excluded from further analysis. In addition, trials that were more than two standard deviations from the individual mean for each response type (joystick vs. keypress) by mapping rule subcondition were removed as outliers. A three-factor, within-subject analysis of variance (ANOVA) was performed on the RTs with Response Type (joystick vs. keypress), Stimulus (expand vs. contract), and Response (proximal vs. distal response) as factors. The mean RTs for these conditions are shown in Figure 1.

The main effect of response type was significant, $F(1, 14) = 150.42, p < .001$, indicating a 50-msec advantage of keypress responses over joystick responses. The main effect of stimulus was significant, $F(1, 14) = 16.70, p < .01$, as was the main effect of response, $F(1, 14) = 17.11, p < .001$. The Response Type $\times$ Response

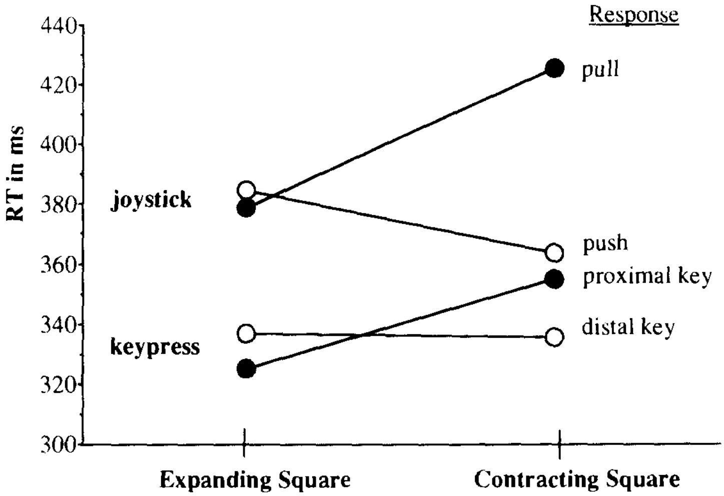

FIGURE 1 Mean RTs in msec for the Stimulus × Response interaction, as a function of the two response types in Experiment 1.

interaction, $F(1, 14) = 12.58, p < .01$, together with Figure 1, reveals that the main effect of response is due to the advantage of push responses over pull responses for the joystick condition. The Stimulus × Response interaction and the three-way Response Type × Response × Stimulus interaction were both significant, $F(1, 14) = 18.85, p < .001$, and $F(1, 14) = 6.18, p < .05$, respectively. The three-way interaction reveals that the size of the compatibility effect was task dependent; it was larger for the joysticks (34 msec) than for the keypress responses (15 msec).

To test for the significance of the compatibility effect for both response types, we performed separate ANOVAs for each response type with Stimulus and Response as factors. For the joystick data, the main effect of stimulus was significant, $F(1, 15) = 10.51, p < .01$; the expanding square was responded to 13 msec faster than the contracting square. The main effect of response was significant, $F(1, 15) = 21.92, p < .001$; distal responses (the pushes) were 29 msec faster, on average, than the proximal ones (the pulls). Further, the Stimulus × Response interaction was significant, $F(1, 15) = 16.40, p < .001$, indicating an overall 34-msec compatibility effect, as plotted in the upper lines of Figure 1. When pulling a joystick, responses were faster to an expanding square than to a contracting square. Conversely, pushing a joystick to a contracting square was faster than to an expanding square.

For the keypresses (the lower lines of Figure 1), the main effect of stimulus was significant, $F(1, 15) = 12.63, p < .01$; responding to the expanding square was 14 msec faster than responding to the contracting square. In addition, the Stimulus × Response interaction was significant, $F(1, 15) = 13.84, p < .01$. This interaction reflects a 15-msec compatibility effect; pressing the distal key to a contracting square, and pressing the proximal key to an expanding square were relatively fast.

In sum, with both response types a compatibility effect was observed, and the size of the effect was significantly larger with joystick responses than with keypress responses.[2]

Discussion. The combination of contracting square–distal response, expanding square–proximal response was faster, on average, than the converse combination. Thus, with both response types, a compatibility effect was observed when the stimulus and the response had the same "value" on the proximal–distal dimension. From this we infer that the optimal description of the expanding or contracting squares is in terms of information about approaching or receding objects, respectively, as hypothesized. Relatedly, we infer that RT differences under different S–R mappings are a function of this information, and not of lower order stimulus characteristics, such as luminance or momentary image size.

A second observation concerns the size of the compatibility effect, which was significantly larger for the joysticks than for the keypresses. The finding of a differential compatibility effect for the two response types is not to be expected from an account solely in terms of positional codes (i.e., proximal and distal) for the two response types. However, the finding is consistent with the expectations that participants are sensitive to information (about approach or recession) in the pattern, and that some actions are more strongly coupled to this information than other actions. Our results suggest that a response involving hand displacement, the joystick deflections, is affected more by stimulus patterns specifying displacement than are positional keypresses, which might be guided by information about the (proximal or distal) "endpoint" of the pattern. This conclusion need not be undermined by our observation of a 50-msec RT advantage of keypress over joystick responses, because the two different movements involved in producing the response (flexing an index finger vs. radial or ulnar abduction of the wrist) make it difficult to directly compare the absolute RTs of these two response types.

Other tentative support for a notion of static–static, kinematic–kinematic compatibility comes from results reported by Proctor, Van Zandt, Lu, and Weeks (1993), who used static and kinematic stimuli. These authors compared (static) arrows pointing left or right, and squares moving left or right on the computer screen as stimuli for left–right keypress responses. Because both stimulus types yielded a compatibility effect, the authors concluded that the effect, in both situations, could be explained by pointing to the relative position of the stimulus, so that "there is nothing special about motion per se in the destination compatibility effect" (p. 89). However, for the condition in which participants had to respond to the left–right

[2]Additionally, to ensure that the difference in the size in the compatibility effects between the two response types was not an artifact of distributional characteristics of the relatively longer RTs of joystick responses, we repeated the same analysis on the medians from the complete data set (that is, including the outliers). The same effects were observed; the size of the compatibility effect for the joysticks was 35 msec, and for the keypresses 13 msec.

"destination" of the stimulus (i.e., respond to the pointing direction of the arrow, or respond to the destination of the moving stimulus), the size of the effect was larger for the arrow stimuli (87 msec) than for the moving squares (72 msec). This 15-msec difference was not put to a statistical test, but it is consistent with the suggestion that a "static" keypress response is more compatible with a (static) arrow stimulus than with an apparent moving one, and, more generally, with the thesis that there is more to "spatial" compatibility effects than relative position.

EXPERIMENT 2

In an attempt to further explore the idea that compatibilities relate to information, we combined task-relevant and task-irrelevant stimulus dimensions that by themselves were not expected to enter into a compatibility relation with the response. The effects of nominally irrelevant dimensions on RT are termed *Simon effects* and have been widely studied and theorized about in the compatibility literature (see Lu & Proctor, 1995, for a thorough review). It is generally found that when an irrelevant stimulus dimension has a commonality with the response (e.g., they can both be classified as left or right), RTs are faster when the irrelevant stimulus dimension and the response (spatially) correspond. The irrelevant dimensions are generally considered as conceptually separate from the relevant dimension (of the imperative stimulus).[3] One might question whether, and to what extent, it is legitimate to a priori "decompose" an environmental pattern into separate dimensions. From an ecological perspective it is likely that, with a particular display, observers are sensitive to higher order variables (e.g., ratios), and that S–R compatibility is a function of these variables. Although environmental patterns admit to a description as a loose collection of elements, a description in terms of information may yield variables that better serve perception and action. The information in such a pattern (though not necessarily its constituent elements) might be compatible or incompatible with responses. Put another way, one might have (task) relevant and (task) irrelevant dimensions of stimulation that independently bear no compatibility relations with one or the other response, but that together do reveal compatibilities. If such can be shown to be the case, it would serve to emphasize the integrity of the informational ensemble, in that the response is compatible with the *information* in the pattern, and not with any of its independent constituents.

In this experiment, we asked participants to push or pull a joystick in response to a stimulus appearing left or right of fixation. In addition to the imperative

[3]Kornblum et al. (1990) labeled the overlap between the relevant and irrelevant stimulus dimension a Type-4 ensemble (that characterizes Stroop-like tasks), and the overlap between the irrelevant stimulus dimension and the response set a Type-3 ensemble (that characterizes Simon-tasks), which seems to imply separate coding of the dimensions.

stimulus, a background was shown on some trials, namely a texture gradient (see Figure 2), so that the stimulus appeared either over the far side or over the near side of the gradient. We reasoned that the distance information provided by the gradient, in spite of its nominal irrelevance to the left–right/push–pull task, would affect the time it takes to initiate the required movement.

Method

Participants and Design. Ten students at the Vrije Universiteit participated. They had to push or pull a joystick as rapidly as possible in response to the location (left or right of fixation) of the imperative stimulus. There were two rules for mapping the location of the stimulus to the response: left–push/right–pull, and right–push/left–pull.

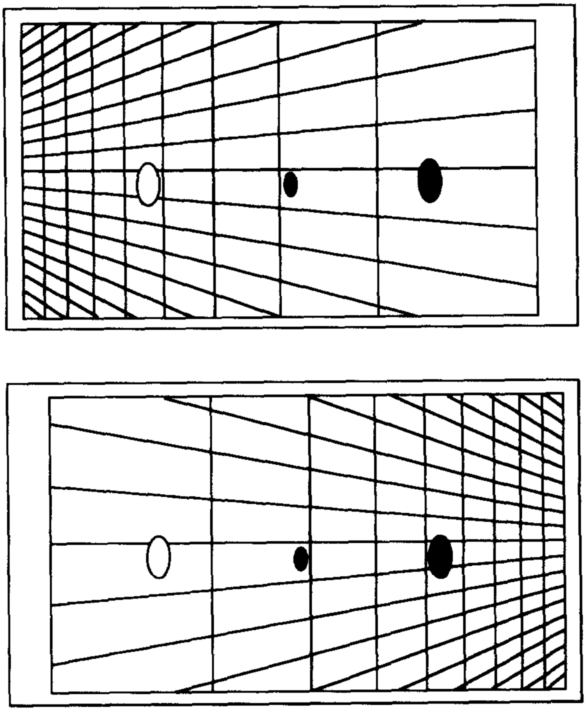

FIGURE 2 The two texture gradients, with an imperative stimulus to the right of fixation. In the upper part of the figure, the stimulus appears over the proximal side of the (proximally right) gradient. In the lower part of the figure, the stimulus appears over the distal side of the (proximally left) gradient. The centrally located ellipse is the fixation point. On the computer screen, the gradient was actually white on black.

Apparatus and stimuli. Stimuli were shown on an AMIGA monitor. The stimulus display consisted of a fixation dot, two stimulus outlines that flanked the fixation dot, and a texture gradient, resembling a wall (see Figure 2). The fixation dot was a red ellipse, 10 mm high and 5 mm wide. The stimulus outlines both consisted of a yellow ellipse, 20 mm high and 10 mm wide. Their centers were 58 mm left or right from the fixation point. The gradient pattern was 130 mm high, and 205 mm wide. Responses were given by pushing or pulling a joystick that was centrally located in front of the monitor.

Procedure. Each trial began with the display of the fixation ellipse, two peripherally located elliptical outlines, and, on two-thirds of the trials, one of the gradient backgrounds (see Figure 2). In the neutral condition the background was absent. After 500 msec, the imperative stimulus appeared—one of the two lateral elliptical outlines was illuminated (filled). If an incorrect response was given, participants heard a beep.

Half the participants performed the first half of the experiment with their left hand, and the second half of the experiment with their right hand. This order was reversed for the other participants. Within each of these blocks, two blocks of trials were presented for the two mapping rules in the same order. The order of mapping rule was balanced between participants. Twenty trials for each combination of location of the imperative stimulus (left or right), and the three background conditions (a plain background and the two gradients in Figure 2) were completely randomized in the mapping rule by responding hand blocks, resulting in a total of 480 trials.

Results. Errors and RTs that exceeded 1,000 msec (together 5.3%) were excluded from further analysis. In addition, trials that were more than two standard deviations from the individual mean were removed as outliers. A four-way, within-subjects ANOVA was performed on the mean RTs, with Hand, Response (push vs. pull), Stimulus Location (left or right of fixation), and Background (none or gradient with the proximal side left, or right) as factors. No main effects were significant. However, two interactions reached significance: the Background × Stimulus Location interaction, $F(2, 18) = 5.55$, $p < .01$, and the three-way Response × Background × Stimulus Location interaction, $F(2, 18) = 4.95$, $p < .05$. The two-way interaction indicates that, on average, a stimulus that appears over the far side of the gradient is responded to faster than a stimulus that appears over the near side of the gradient. The three-way interaction indicates that this effect depends on whether the response was a push or a pull. To further explore this interaction, separate ANOVAs were performed on the two response types. For the pull responses, no effects were significant. For the push responses, the Background × Stimulus Location interaction was significant, $F(2, 18) = 12.836$, $p < .001$. This interaction suggests that pushes were faster when the stimulus appeared over the far side of the gradient and slower when it appeared over the near side (see Figure 3).

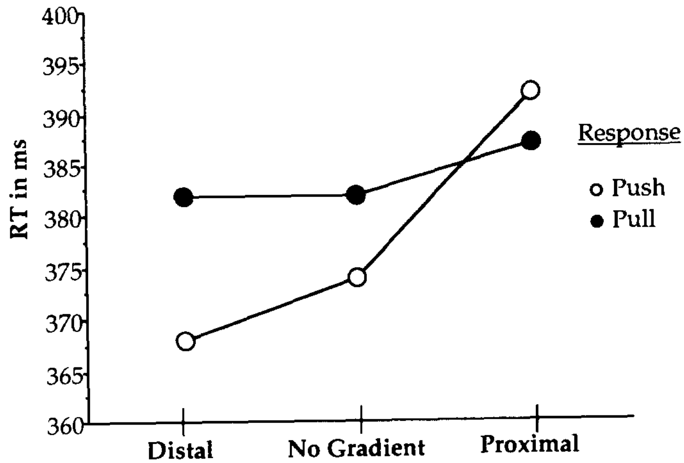

FIGURE 3 Mean RTs in msec for the Stimulus Location × Background × Response interaction, averaged over stimulus location (left or right), as a function of background condition. Note: "Distal" refers to the condition where the stimulus appears over the far side of the gradient (the lower part of Figure 2), and "proximal" refers to the condition where the stimulus appears over the near side of the gradient (the upper part of Figure 2).

Discussion. There was a clear-cut compatibility effect; pushing a joystick to an ellipse that appears over the "far side" of the gradient is faster than giving the same response to a stimulus that appears over the near side of the gradient. With pull responses, on the other hand, no such effect occurred. We note, first, that the direction of the compatibility effect is consistent with the notion of grid regarding information about position. As in Experiment 1, the events or circumstances (3-D motions or positions) specified by information, rather than geometric (or kinematic) elements per se, rationalizes the compatibility effects.

In that a nominally irrelevant variable, gradient orientation, affects RT, the observed compatibility effect might be considered to be a typical Simon effect. It is not a typical effect, however, because grid orientation by itself is not differentially compatible with the push and pull actions. Nor is there an explanation to be had on the basis of S–S congruity, because the effect appeared to be contingent on response type. Rather, a compatibility effect only shows up with a specific combination of the gradient, the location of the stimulus, *and* the required response. The scene depicted by the information appears to afford pushing. In this respect, the virtual absence of a compatibility effect for the pull responses is also telling. Pulling a joystick in this situation does not appear to be differentially affected by the available information; the coupling is less compatible. Thus, it appears that the overall S–R situation in this experiment constitutes an information–action compatibility in which the information, although arguably composed of two stimulus characteristics, cannot be reduced to them.

The findings from our experiment resemble an observation by Hommel and Lippa (1995), who had participants make a speeded left–right response to a stimulus superimposed on the eyes of an image of Marilyn Monroe's face. On some occasions, the face was tilted 90° or 270°, so that the stimulus appeared above or below fixation. It was found that left responses to stimuli on the "left" eye, and right responses to stimuli on the "right" eye (i.e., relative to the orientation of the face) were initiated relatively fast. Hommel and Lippa explained this compatibility effect in terms of the participants' "referential coding" of the stimulus material relative to the context, so that, say, a below stimulus *plus* a 90° face tilt (the context) yields an interpretation of a right stimulus. In other words, the leftness or rightness of a stimulus was argued to be a function of the perceiver's processing mechanisms. We would interpret the results differently—the location of the stimulus resides in the lawful relation between the orientation of a face and the orientation of the eyes, in that a left eye will still be a left eye when the head is tilted to an angle of 90°. When confronted with the pattern of stimulation (face and eyes), the perceiver can detect certain information about position because the identity of something (an eye being a *left* eye) remains invariant under a certain set of transformations. As regards predictions, of course, the two interpretations are equivalent.

EXPERIMENT 3

Experiments 1 and 2 demonstrated that a stimulus qua information pattern can participate in compatibility effects, in that the RT differences could be related to certain higher order characteristics of the pattern that presumably served as the effective stimulus. Experiment 3 was designed as an action complement to Experiments 1 and 2, to demonstrate that a description of responses qua action might provide a basis for rationalizing certain compatibility phenonema. It was expected that RT differences obtained under different S–R mappings would be a function of certain low-dimensional characteristics of the response (i.e., the intended *goal* of the response). To this end, we decided to perform a modified version of an experiment by Guiard (1983), in which a limb movement in a particular direction could be understood as effecting either of two goals.

Guiard reported a set of choice RT experiments, in which participants had to rotate a steering wheel as quickly as possible in one direction or the other in response to a low-pitched or high-pitched auditory stimulus. The stimulus was presented to either the left or the right ear: an "irrelevant stimulus dimension." From the work of Simon and Rudell (1967), we know that irrelevant position of an auditory stimulus exerts a Simon effect, in that spatial S–R correspondence generally speeds up the response. The conditions of Guiard's Experiment 3, in which participants held the wheel bimanually at the 6:30 (bottom) position, are the most interesting, because in this situation the "leftness" and "rightness" of the response can be in terms of either a particular hand movement, or in terms of the turning direction of the wheel. The question Guiard asked was whether the spatial characteristics of the hand movements or the spatial characteristics of the wheel rotations would enter into a Simon effect with the stimulus. The data of his Experiment 3 suggested that there were two types of participants; one group appeared to be faster when the left–right movement of the hands coincided with the task-irrelevant position of the stimulus, and another group appeared to be faster when the left–right turning direction of the wheel (i.e., the direction of the top of the wheel) coincided with the position of the stimulus.

In our experiment, we tried to replicate Guiard's findings, but with a spatial compatibility task. Our participants were asked to respond to the (task-relevant) left–right position of a visual stimulus. The response device consisted of a steering wheel that had to be rotated in a particular direction as quickly as possible in response to the position of a visual stimulus. It was expected that individuals might differ from each other in the compatibility effects they demonstrate with the 6:30 hand placement; some might be faster when the wheel rotated in the same direction as the stimulus (which we call a "wheel-compatibility" effect), and some might be faster when their (left–right) hand movement was in the same direction as the stimulus (a "hand-compatibility" effect). We interpret a hand-compatibility effect as a response qua limb movement, and a wheel-compatibility effect as a response qua manipulation of the response device.

In addition, with the 12:00 hand placement we expected a "standard" spatial compatibility effect, in that spatial S–R correspondence will speed up RT relative to an S–R mapping involving spatial noncorrespondence. Notice that at the 12:00 position, hand-compatibility and wheel-compatibility coincide.

Method

Participants. Sixteen students at the Vrije Universiteit of Amsterdam participated. They were all right-handed, and they were paid a small fee for their participation.

Apparatus and stimuli. Participants were seated at a table, into which a steering wheel with a 38 cm diameter was mounted horizontally. The distal end of the table was raised to a 5.5° angle, to facilitate grasping the top of the wheel. Bands of rubber were attached to the sides of the wheel so that the wheel automatically returned to its initial position. Attached to the axis of the wheel was a 12-bit potentiometer that registered the displacement of the wheel at a frequency of 200 Hz. Reaction time was defined as the interval between the onset of the imperative stimulus and a 2-cm displacement of the wheel.

The imperative stimulus was presented on a horizontally oriented bow of light-emitting diodes (LEDs), positioned in front of the table, approximately 22 cm below eye height. The imperative stimulus consisted of the illumination of a red LED, 25 cm to the left or to the right of the center of the bow. The distance between the distal end of the wheel and the center of the bow was 87 cm. The vertical distance between the distal end of the wheel and the center of the bow was 24 cm.

Procedure and design. Participants rotated the wheel with either their left or their right hands, depending on condition. The responding hand was positioned either distally (the 12:00 position) or proximally (the 6:30 position). Participants were asked to make a fast movement with the wheel in response to the (left or right) occurrence of the imperative stimulus, under each of two S–R mapping rules. We labeled the mapping in which the response resulted in a displacement of the *distal end* of the wheel in the same direction as the stimulus as steering-consistent, and the converse mapping as steering-inconsistent, irrespective of hand position.

Each trial started with a warning signal; the central LED was illuminated for 1,000 msec. After a 500 msec interval, the left or right stimulus LED was illuminated for 500 msec. The interval between the occurence of a response and the start of the next trial was about 3 sec, the time required for the computer to store the data and generate the next trial. When an incorrect response was made, a beep was heard.

In explaining the required movement, the terms "left" and "right," or "toward the stimulus" and "away from the stimulus," were avoided in the instruction so as to prevent inducing a bias in attending to a particular spatial correspondence. Instead, the experimenter simply pointed out the required movement at the beginning of each block of trials ("with this light, make this movement, and with that light, make that movement"). Participants were free to choose the amplitude of the movement.

The experiment consisted of eight blocks of trials (2 hands, 2 hand positions, and 2 mapping rules). Each hand received the two hand positions and the two mappings in a random order. Hand order was also random. Each subcondition consisted of 60 trials, resulting in a total of 480 trials. At the beginning of each block, participants received verbal instructions, and they were given 5 practice trials that were not further analyzed. Participants had the opportunity to perform an additional 5 practice trials, which was requested on only a few occasions. The entire experiment lasted about 70 min. Halfway through the experiment, participants could take a short pause.

Results. Errors and RTs that were outside the range of 150–1,000 msec (1.7 % in total) were not further analyzed. A three-factor within-subjects ANOVA was performed on the mean RTs with Hand (left vs. right), Hand Position (proximal vs. distal), and S–R Mapping (steering-consistent vs. steering-inconsistent mapping) as factors. The mean RTs for each subcondition, averaged over all participants, are shown in Table 1.

Only two effects reached significance; the main effect of S–R mapping, $F(1, 15) = 5.205$, $p < .05$, indicating a 16 msec advantage, on average, for the steering-consistent S–R mapping over the steering-inconsistent one; and the S–R Mapping × Hand Position interaction, $F(1, 15) = 17.035$, $p < .001$, indicating that the mapping effect was contingent on hand position. For the distal hand position, the RTs for the steering-consistent and steering-inconsistent S–R mapping were 372 and 418 msec, respectively, indicating that movements in the direction of the stimulus were initiated faster than movements in the other direction. For the proximal hand position, however, this pattern of results seemed to be reversed; the RTs for the steering-consistent and steering-inconsistent S–R mapping were 413 and 400 msec, respectively. Thus, with the proximal hand position, RTs were somewhat faster when the position of the stimulus coincided with the direction of movement of the *hand*, instead of the direction of rotation of the wheel.

To test for the expected individual differences, we performed separate ANOVAs for each participant's distal and proximal hand placements, with S–R Mapping and Hand as factors. As can be seen from Table 2, all participants demonstrated the same significant compatibility effect with the distal hand position: Hand movements–wheel rotations in the direction of the stimulus were initiated faster than movements–rotations in the direction opposite to the stimulus. With the proximal hand position, however, there were large individual differences with respect to the presence or absence of a compatibility effect, and the direction of the effect. Nine of the 16 participants showed a hand-compatibility effect; hand movements in the direction of the imperative stimulus were initiated faster than movements in the other direction, and four participants showed a wheel-compatibility effect; wheel rotations in the direction of the stimulus were initiated faster than rotations in the other direction. Finally, three participants showed no significant difference between mappings.

TABLE 1
Mean RTs (in Msec) for Each Subcondition of Experiment 3

	Mapping and Hand			
	Left		*Right*	
Hand Position	*Consistent*	*Inconsistent*	*Consistent*	*Inconsistent*
Proximal	421	410	405	390
Distal	375	428	370	412

TABLE 2
Mean RTs (in Msec) of Experiment 3 for Both Mappings and Hand Positions

	Hand Position					
	Distal			*Proximal*		
Participant	I	C	I-C[a]	I	C	I-C[a]
1	480	437	43*	424	470	–46*
2	380	367	13*	357	380	–23*
3	370	330	40*	324	401	–77*
4	410	325	85*	327	412	–85*
5	396	364	32*	360	417	–57*
6	384	337	47*	369	399	–30*
7	328	303	25*	313	344	–31*
8	428	353	75*	462	382	80*
9	365	343	22*	437	378	59*
10	451	388	63*	540	459	81*
11	345	311	34*	319	358	–39*
12	463	408	55*	450	441	–8
13	364	352	12*	384	347	37*
14	457	387	70*	397	412	15
15	517	465	52*	466	527	–61*
16	555	485	70*	471	477	6

Note. *I* = steering-inconsistent; C = steering-consistent. The asterisk indicates the presence of a significant (.05) main effect of mapping in a two-way S–R Mapping × Hand ANOVA.
[a]Indicates magnitude and direction of the compatibility effect (steering-inconsistent–steering-consistent), averaged over hand.

Discussion. The results of this experiment demonstrate a clear-cut compatibility effect with the distal hand position; wheel rotations–hand movements in the same direction as the stimulus were initiated faster than rotations–movements in the other direction.

Note that with the distal hand position, it is not possible to tell whether the compatibility effect resides in a faster hand movement or in a faster wheel rotation in the direction of the stimulus. With the proximal hand position, however, the left–right direction of hand movement and the left–right rotation of the response device were dissociated. The results suggested that, with the proximal hand placement, some participants initiated their responses faster when their *hand* was to be moved in the same direction as the stimulus, whereas others initiated their responses faster when they were to turn the wheel in the same direction as the stimulus, which parallels the results of Guiard's (1983) Experiment 3. Apparently in both experiments, what was a compatible mapping for some participants was an incompatible mapping for others. It therefore seems reasonable to assume that the participants who exhibited sensitivity to a particular correspondence also performed different *acts*, in the sense of trying to attain different goals. One might infer that the participants who showed a hand-compatibility effect had the intention to move their hand as quickly as possible in the same or the other direction as the stimulus, whereas the participants who showed a wheel-compatibility effect had the intention to rotate the wheel in a particular direction.

An intention to perform a certain action can also be manipulated by the instructions participants receive, as evidenced in a clever experiment by Hommel (1993). In Hommel's Experiment 1, participants had to press a left–right key in response to the pitch (high–low) of an auditory stimulus that was presented randomly either to the left or to the right ear. Thus, ear stimulated was the task-irrelevant stimulus dimension. In Hommel's experiment, each (left or right) key press also automatically resulted in the illumination of a left or a right light. Participants always knew the spatial relation (congruent or incongruent) between the keypress and the light. Hommel's manipulation consisted of giving one of two different instructions to his participants. One group was instructed to press the (left–right) *key* in response to the pitch of the stimulus, whereas the other group was instructed to illumimate the (left–right) *light*. Both groups exhibited significant Simon effects; the group that received the "response key" instruction was faster when key and stimulus spatially corresponded, whereas the group that received the "response light" instruction was faster when light and stimulus spatially corresponded.

Together these sets of findings favor a conceptualization of responses as goal-directed actions intended to produce certain environmental effects. This effect might involve the own body (e.g., pushing a button, or moving a glass), or an extension of the own body (e.g., poking with a stick, writing, wayfinding with a cane, etc.). Further, an action seems a better concept for S–R compatibility than simply a movement or a response.

GENERAL DISCUSSION

Experiment 1 demonstrated that of the possible geometric and kinematic descriptors, the descriptor of "patterns specifying an approaching or receding object" best captured the "stimulus" (viz., the information with which the actions were compatible). The RTs of push responses and distal keypresses to receding squares, and pull responses and proximal keypresses to approaching squares, were relatively short. In Experiment 2, a compatibility effect was observed with nonmoving left–right stimuli on a textured background; pushes were relatively fast to stimuli superimposed on the dense part of a texture gradient. Almost no effect was observed for the pull responses. As in Experiment 1, the relevance of various descriptions of the background can be evaluated. The nature of the observed compatibility effect depended, we argue, on the relative distance specified by the background, and presumably not on the two-dimensional shapes and sizes of the grid elements per se. Finally, Experiment 3 demonstrated that of the possible descriptors of a particular response, sometimes a description qua limb movement, and sometimes a description qua manipulation of the response device appeared to lay a basis for the observed compatibility effects.

Two conclusions can be drawn with respect to S–R compatibility. First, it is with information that actions are compatible rather than with rudimentary (left–right) stimulus elements per se. This is in line with Bootsma's (1988) observation that experienced soccer players, who were confronted with slides of a penalty kicker about to make contact with the ball, accurately perceived the corner of the net in which the ball would enter. When participants had to give a left–right response, in a choice RT task, to the destination (left–right) of the ball, the congruent mapping situation (left to left and right to right) yielded shorter RTs than the converse mapping. But note that the destination information is available only from the striker's posture relative to the ball, just before ball contact. Destination was not specified by any leftness or rightness of elements in the photographs.

Our results direct attention toward the physical characteristics of the stimulus at an appropriate level of description. This interpretation stands in contrast to Alluisi and Warm's (1990) claim that the effects of the physical (as opposed to conceptual) correspondence between stimuli and responses is probably "artifactual," and "overly limiting" (p. 5). Compatibility effects that cannot be described in the language of physical correspondence, so their argument goes, result from a conceptual correspondence. However, Alluisi and Warm (1990) employ a restricted view on "physical correspondence," a view that is based on relatively low level physical descriptors. But Alluisi and Warm's conceptual level can be interpreted as a *perceptual* level, tightly coupled to an appropriate physical description. We emphasize the goal of identifying the information that supports the perceptual level, and how that description is lawfully related to the unfolding actions of the organism.

Our second conclusion is that a researcher's selection of a discriminative response is nontrivial. With respect to choice RT, our Experiment 1 showed that the size of the compatibility effect is determined by the nature of the response, even though the two response types (joystick and keypress) both involved proximal and distal movements; overall, the compatibility effect was smaller for the keypresses than for the joysticks. Experiment 2 suggested that push responses, which showed a large effect of gradient orientation, and pull responses, which did not, are not simply opposites (see also Tipper, Lortie, & Baylis, 1992). Finally, Experiment 3 demonstrated that what appeared to be the same left–right movement could enter into different compatibility relations, presumably depending on the intention to produce a particular effect (turning the wheel or moving a limb). These findings seem to imply that higher order properties of an action (perhaps its functional significance) are the characteristics that can be said to be compatible with the available information.

An operationalization of a pair of responses as, say, left and right, might not do full justice to the intended act. As an example, Chon and Michaels (1991) had participants make a left–right bimanual response in a standard compatibility paradigm. On some occasions a mild electrical shock was delivered to one of the responding hands. The results showed that release responses were faster in avoiding or terminating a shock to the same hand, whereas press responses were faster in avoiding or terminating a shock to the other hand. Presses appeared to be more suited for "operating," and releases appeared to be more suited for "withdrawal." Which of the characteristics captures what participants "are actually doing" when they perform a particular movement (push, pull, rotate, press, etc.) is an empirical question, but our examples serve to illustrate the importance of providing a description of "responses" in terms of goal-directed actions. These considerations lead to the prediction that actions that fall within the same equivalence class (or that are "functionally specific," in Reed's 1982 terminology) should also exhibit similar compatibility effects, despite differences in the particular movements that give rise to the action. Recently, we (Stins & Michaels, 1997), performed a set of choice RT experiments in which participants had to reach to a position on a board in response to a left–right visual stimulus. The target of the movement was either the illuminated stimulus itself, or another position—the unilluminated stimulus light. Experiments 1 and 2 demonstrated that reaches toward the stimulus were initiated relatively fast, irrespective of the hand (left or right), or the direction of the reach (ipsilateral or contralateral).

In conclusion, we claim that activity is guided by structured patterns of stimulation (information), and that this is true both in the real world and the RT laboratory. Our first two experiments revealed that such patterns (about direction of motion in Experiment 1, and distance in Experiment 2) were the variables that determined the compatibility effects. The second conclusion is the action parallel: not all actions that can be said to occupy some position on a lower order dimension (e.g., proximal–distal keypresses vs. joystick deflections, or left–right movements of a response device) are equivalent, and, moreover, anterior and posterior joystick movements are not simply opposites (Experiment 2). What precisely those higher order dimensions of action are awaits a better understanding of the nature of coordinated activity (see Turvey, 1990), but our research seems to indicate that S–R compatibility is an instance of information–action compatibility, as envisioned by proponents of ecological psychology. If so, differences in response latency may provide at least a crude metric of the efficacy with which a given action can be modulated by a particular source of perceptual information.

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